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LATERAL HEAT FLOW EFFECTS ON THERMOGRAPHIC SENSITIVITY

Ignacio Perez, Paul Kulowitch

NAVAL AIR WARFARE CENTER
AIRCRAFT DIVISION, PATUXENT RIVER, MD

THE SECOND JOINT NASA/FAA/DoD
CONFERENCE ON AGING AIRCRAFT

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PUBLIC AFFAIRS OFFICE
NAVAL AIR SYSTEMS COMMAND

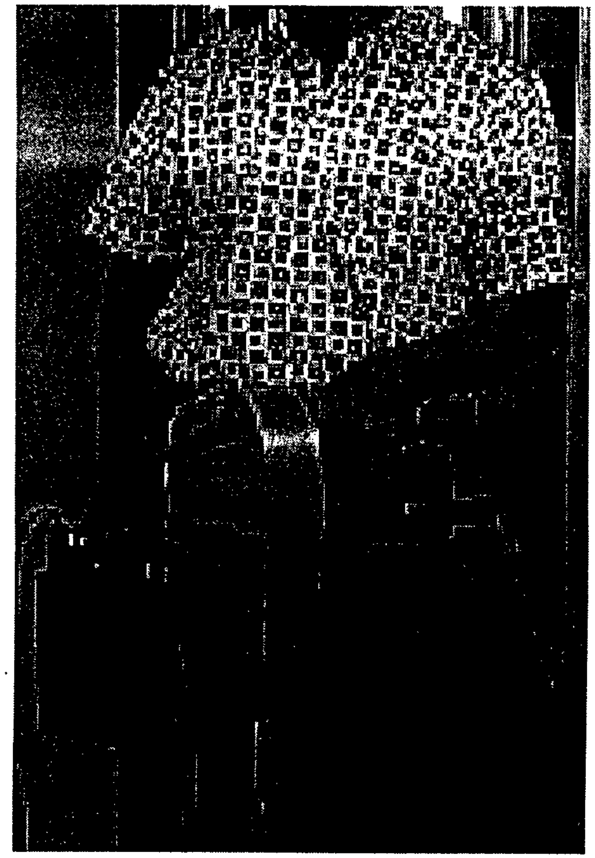
H. Howard

NAVAL AVIATION SYSTEMS TEAM

PORTABLE IR CAMERA SYSTEM

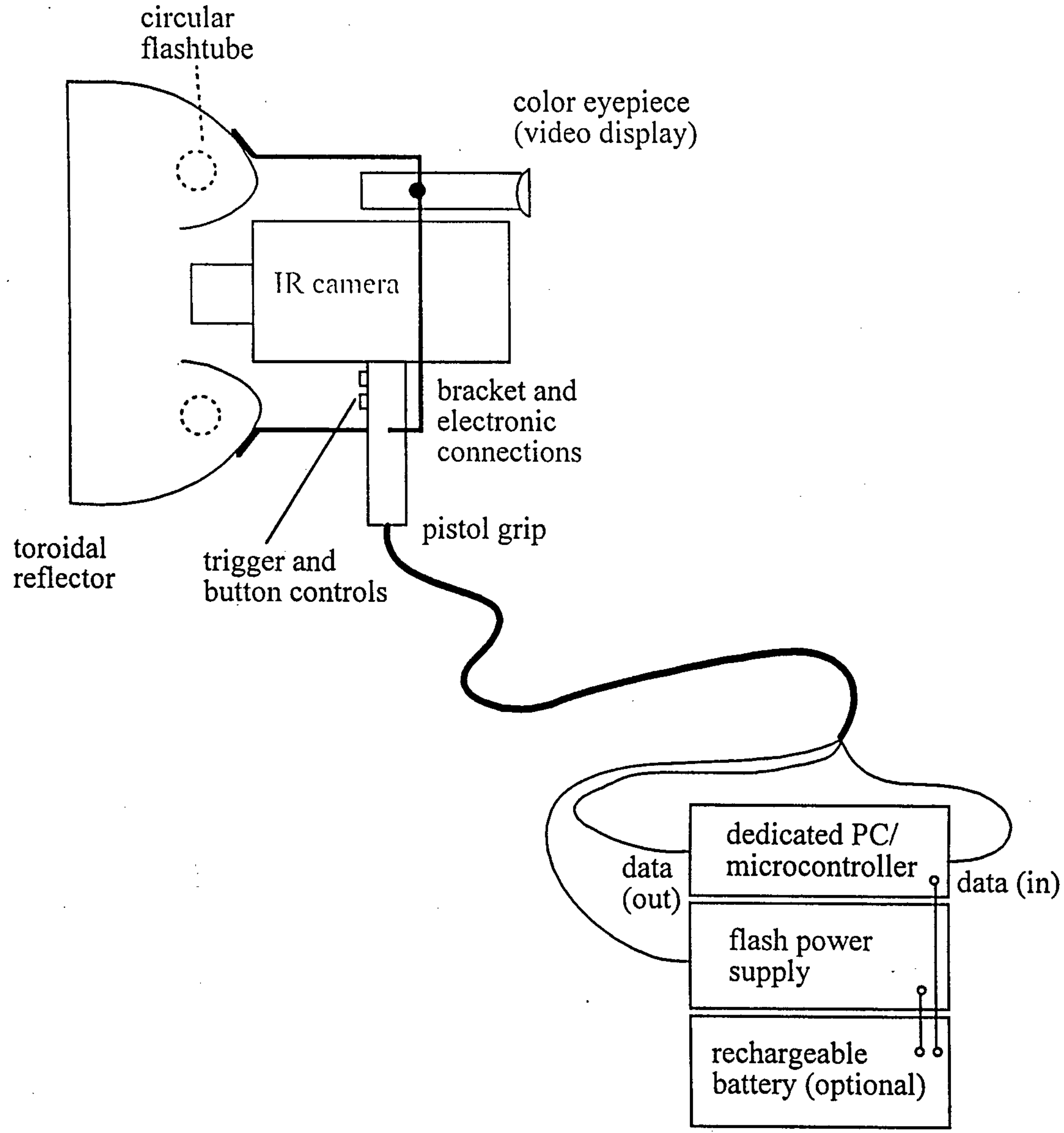
NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING

CAMERA HEAD

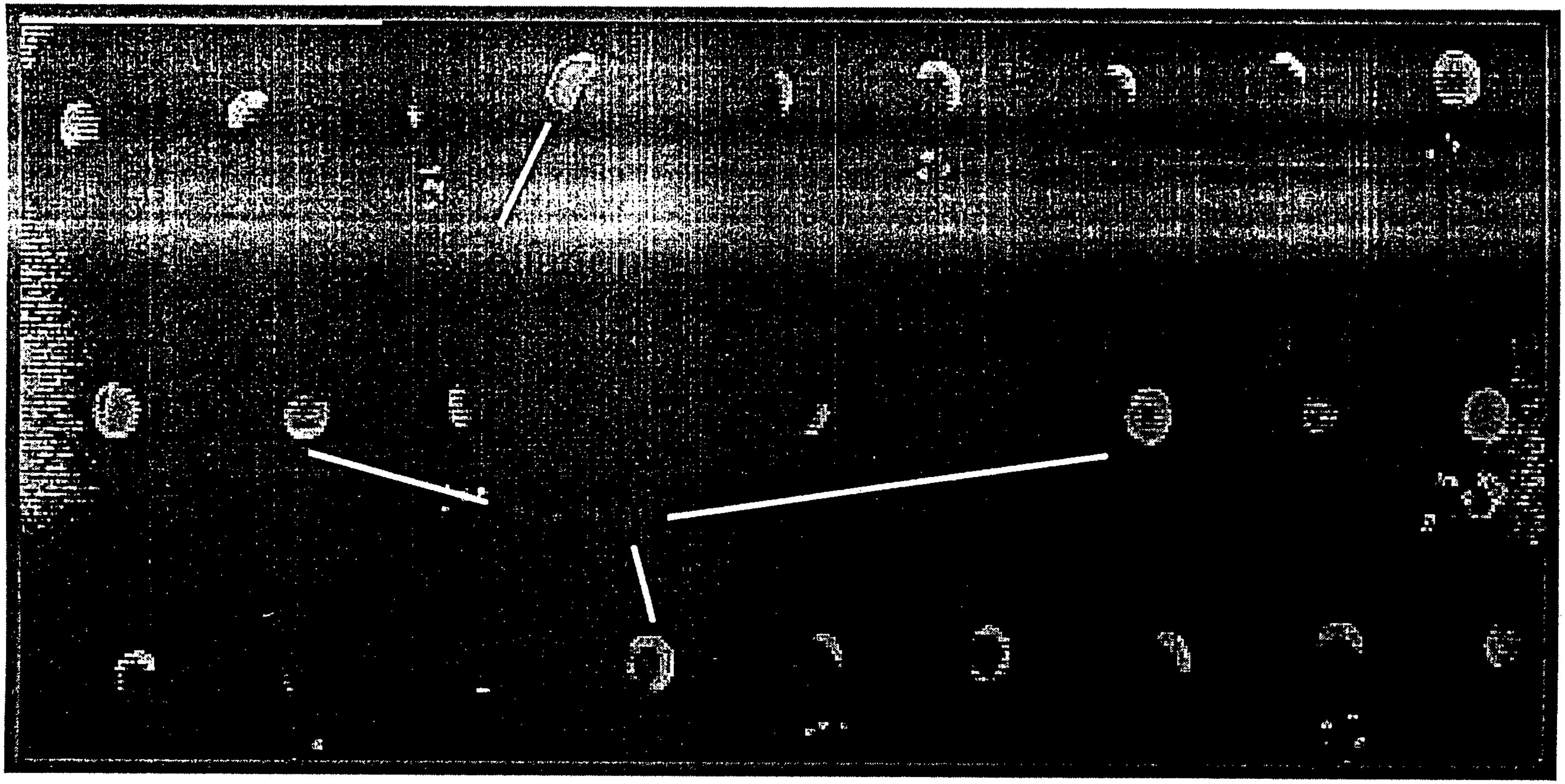


AND POWER SUPPLY

PORTABLE IR CAMERA SYSTEM



CORROSION DETECTION

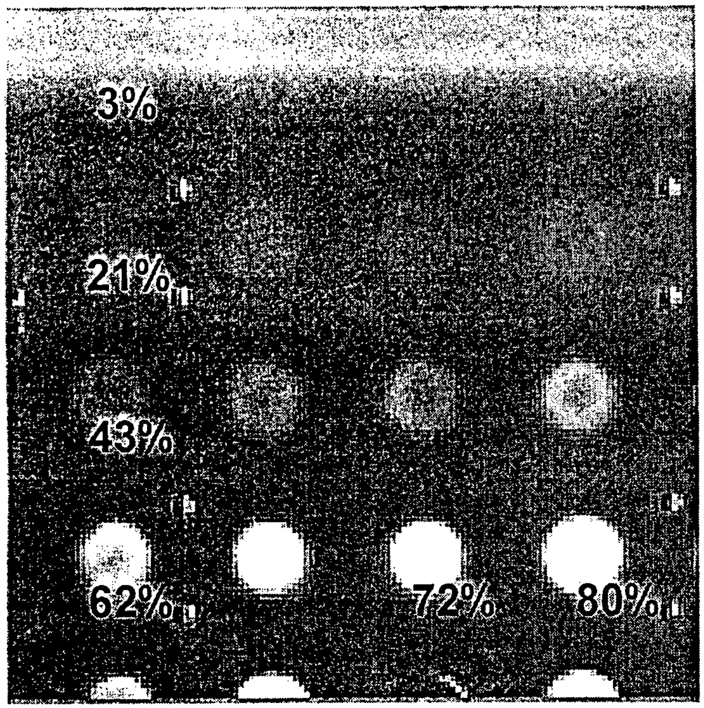


NAVAL AVIATION SYSTEMS TEAM

TEST PANEL & TYPICAL TIME-RESPONSE CURVES

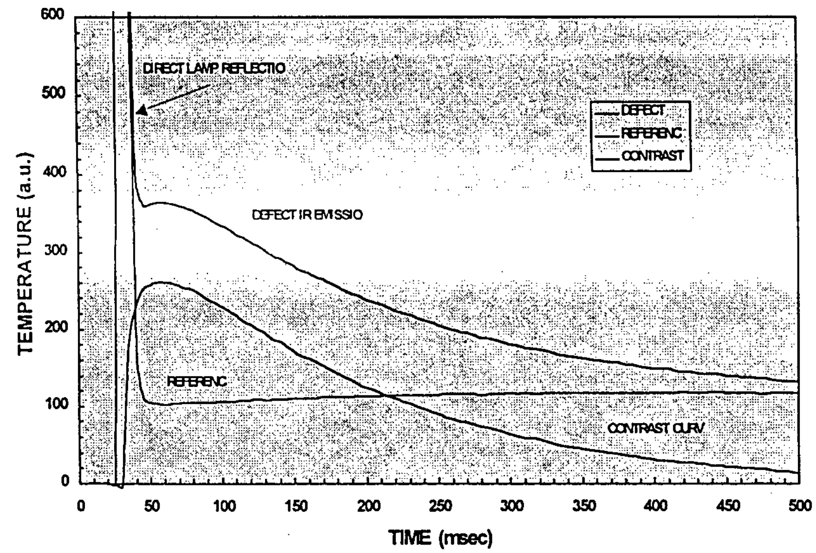
NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING

1/8" Thick Al-7075 panel

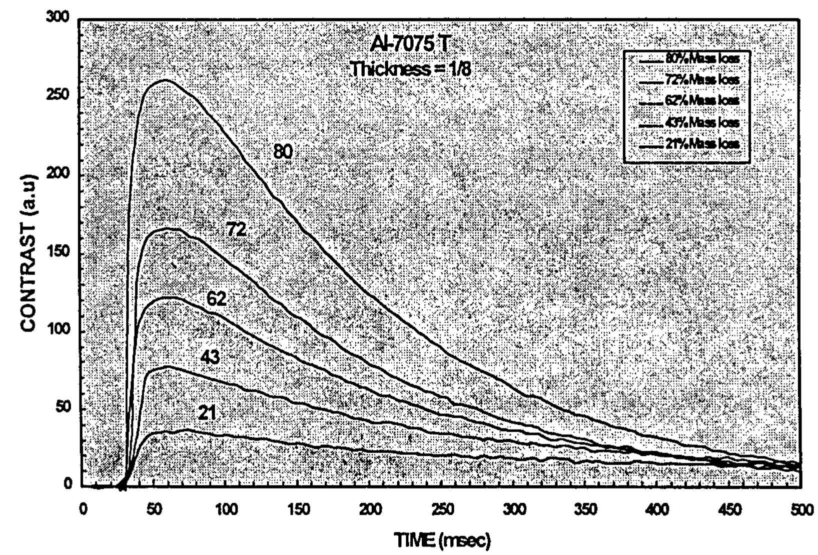


1" Diameter Holes

TEMPERATURE TIME SEQUENCE

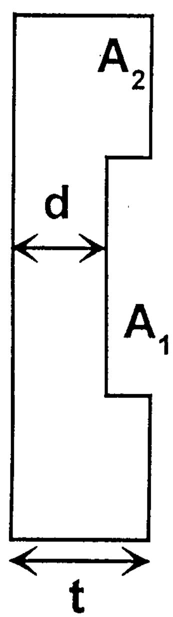


CONTRAST CURVE

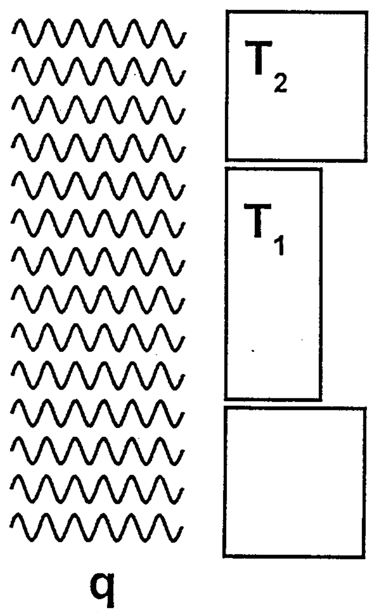


NO LATERAL HEAT CONDUCTIVITY APPROXIMATION

FLAT BOTTOM HOLE



NO LATERAL CONDUCTION APPROXIMATION



$$q = m \cdot c \cdot \Delta T$$

$$q_2 = \rho \cdot A_2 \cdot t \cdot c \cdot T_2$$

$$q_1 = \rho \cdot A_1 \cdot d \cdot c \cdot T_1$$

$$\boxed{\Delta T = \frac{Q}{\rho \cdot c}\left(\frac{1}{d} - \frac{1}{t}\right)}$$

$\Delta T = T_1 - T_2$

$Q = q/A$

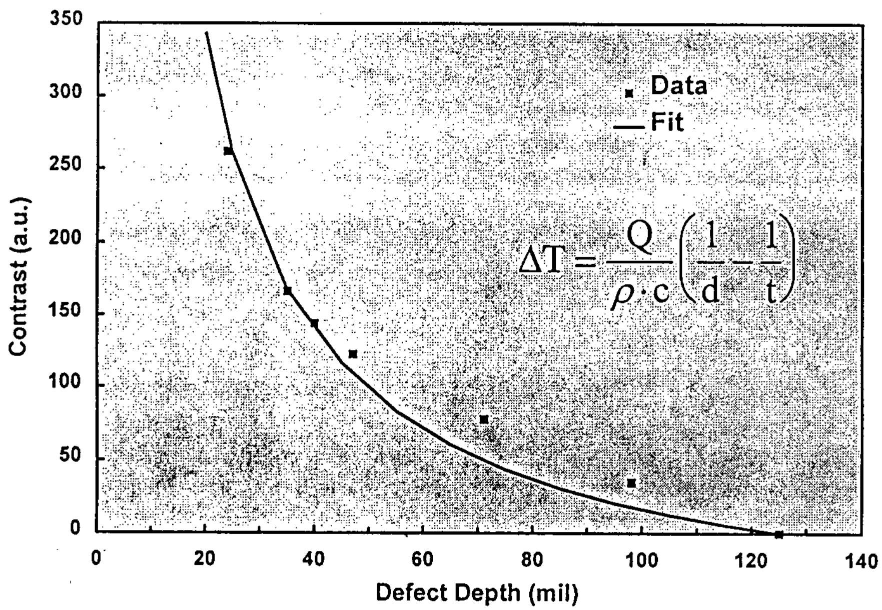
CONTRAST PROPERTIES

$$\Delta T = \frac{Q}{\rho \cdot c}\left(\frac{1}{d} - \frac{1}{t}\right)$$

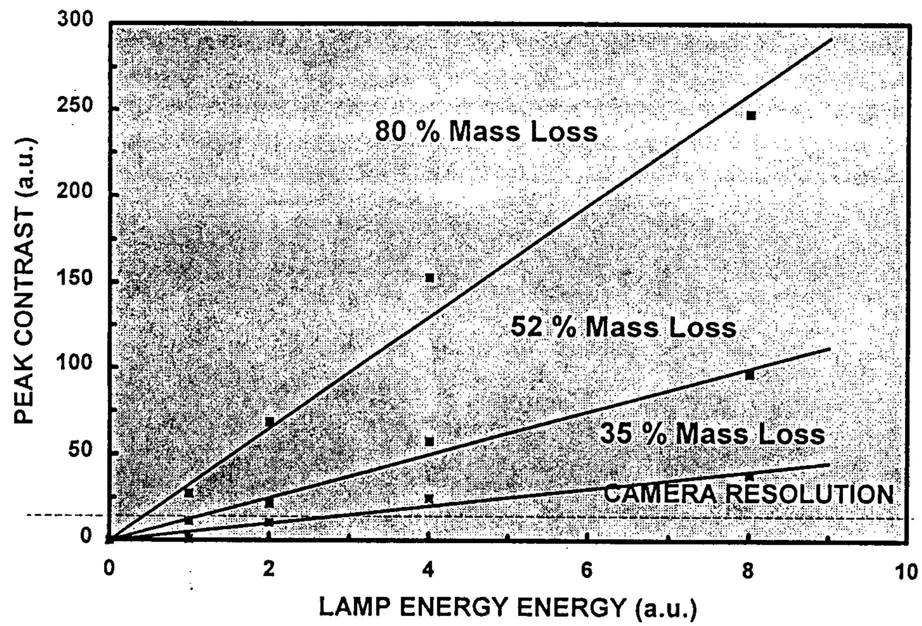
1. THE CONTRAST (ΔT) INCREASES LINEARLY WITH THE AMOUNT OF DEPOSITED ENERGY PER UNIT AREA (Q).
2. THE HIGHER THE SPECIFIC HEAT-DENSITY OF A MATERIAL ($\rho c\uparrow$) THE SMALLER THE PEAK CONTRAST ($\Delta T\downarrow$)
3. THE CLOSER THE DEFECT TO THE SURFACE ($d \rightarrow 0$) THE HIGHER THE PEAK CONTRAST ($\Delta T \rightarrow \infty$).
4. AS THE DEFECT DEPTH APPROACHES THE PANEL THICKNESS ($d \rightarrow t$) THE CONTRAST VANISHES ($\Delta T \rightarrow 0$).
5. FOR A GIVEN DEFECT DEPTH D, THE THICKER THE PANEL ($t \rightarrow \infty$) THE LARGER THE CONTRAST ($\Delta T \rightarrow Q/\rho c d$).

SIMPLE MODEL CORRELATION
(no lateral heat flow)

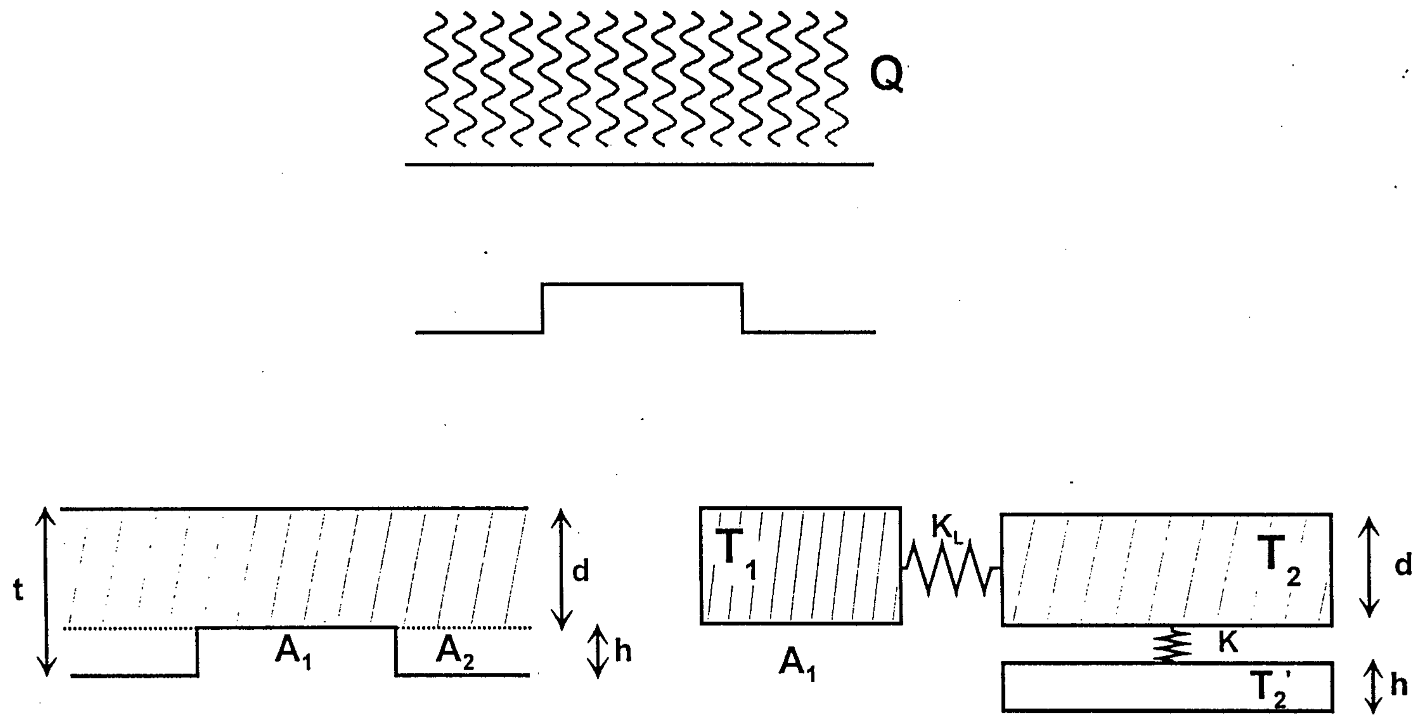
CONTRAST vs DEPTH



DEPTH OF RESOLUTION vs ENERGY



LATERAL HEAT FLOW MODEL



$$\rho \cdot A_1 \cdot d \cdot c \cdot \frac{dT_1}{dt} = k_L \cdot \frac{A_L}{R}(T_2 - T_1)$$

$$\rho \cdot A_2 \cdot d \cdot c \cdot \frac{dT_2}{dt} = k_L \cdot \frac{A_L}{R}(T_1 - T_2) + k \cdot \frac{A_2}{d+h}(T_2' - T_2)$$

$$\rho \cdot A_2 \cdot h \cdot c \cdot \frac{dT_2'}{dt} = k \cdot \frac{A_2}{d+h}(T_2 - T_2')$$

k = Thermal Conductivity

k_L = Lateral Thermal Conductivity

NAVAL AVIATION SYSTEMS TEAM

LATERAL HEAT FLOW EFFECTS

NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING

$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1 - a + r)} \left(e^{-\frac{a}{d(d+h)}\frac{k}{\rho c}t} - e^{-\frac{1+r}{d(d+h)}\frac{k}{\rho c}t} \right)$$

$$t_{max} = \frac{\rho c}{k} \frac{d \cdot t_o}{1 - a + r} \ln \frac{1+r}{a}$$

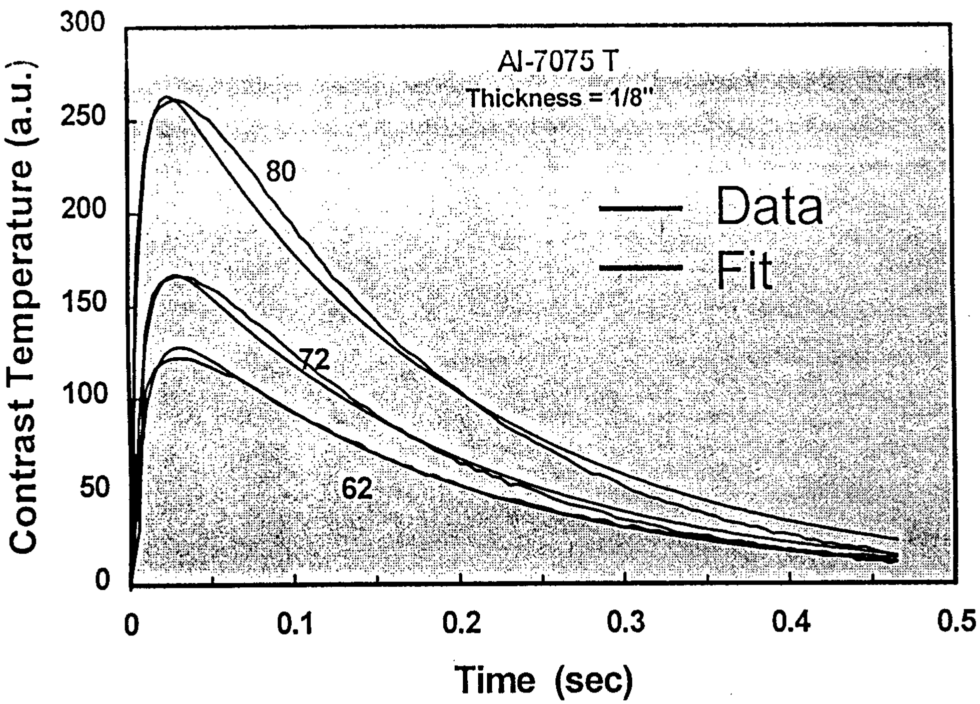
$$\boxed{\Delta T_{max} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right) \cdot \underbrace{\left(\frac{a \cdot h}{t_o}\right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}}_{\text{LATERAL HEAT FACTOR}}}$$

$$a = \frac{k_L}{k} \frac{A_L}{A} \frac{d+h}{R}$$

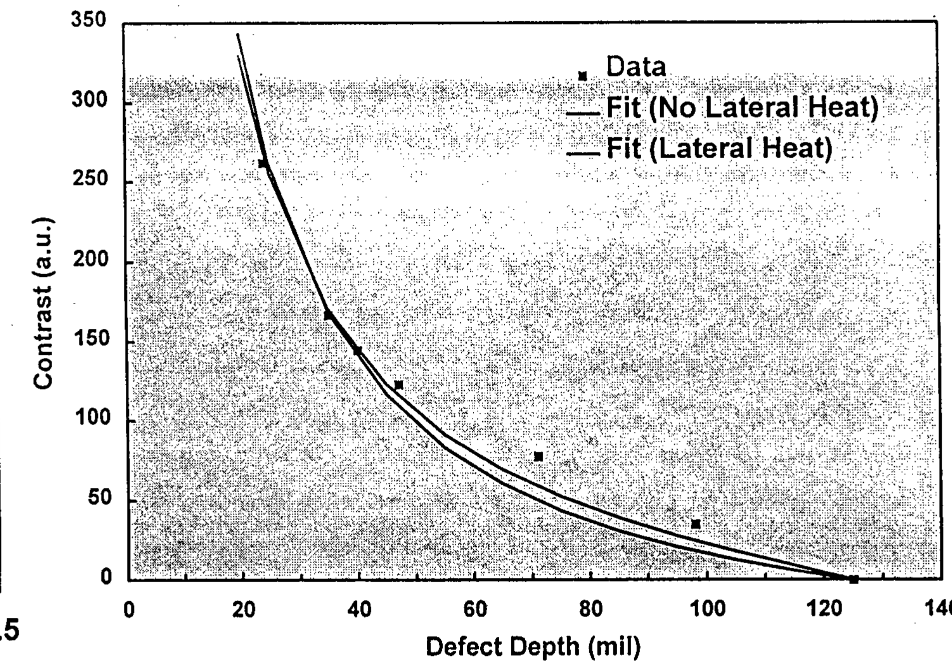
$$r = \frac{d}{h}$$

THERMAL CONTRAST PREDICATIONS

Fit of Contrats Curves



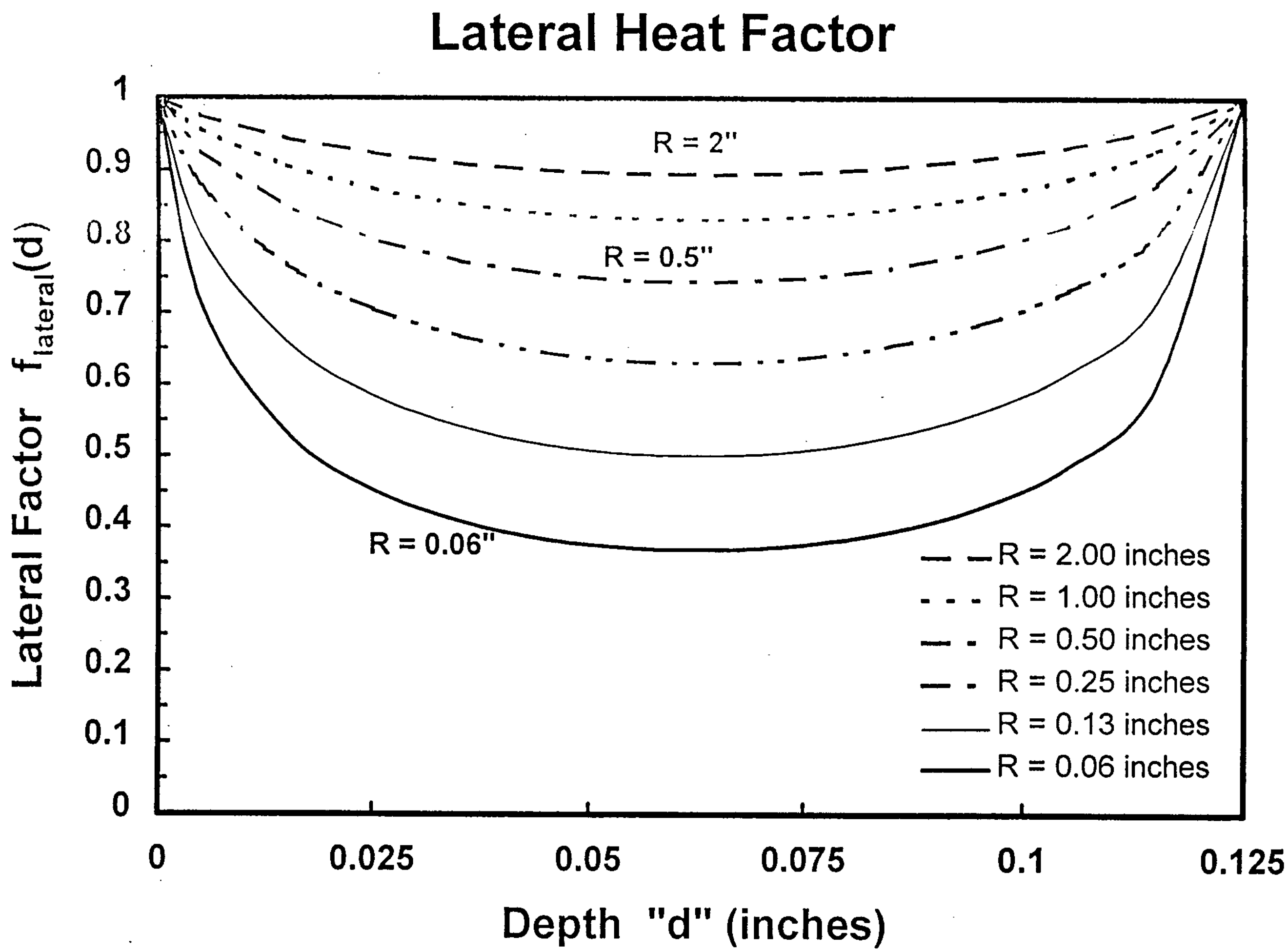
CONTRAST vs DEPTH



$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1-a+r)}\left(e^{-\frac{a}{d(d+h)}\frac{k}{\rho c}t} - e^{-\frac{1+r}{d(d+h)}\frac{k}{\rho c}t}\right)$$

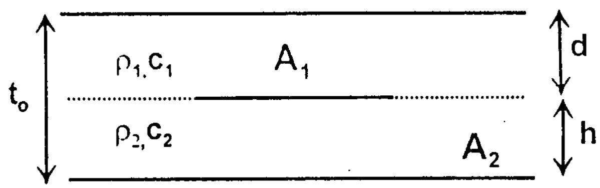
$$\Delta T_{max} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right)\cdot\left(\frac{a \cdot h}{t_o}\right)^{\frac{1}{\frac{t_o}{a \cdot h}-1}}$$

LATERAL HEAT FACTOR
(effective contact conductivity model)



$$\Delta T_{max} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right) \cdot \left(\frac{a \cdot h}{t_o}\right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$

OTHER MODELING RESULTS



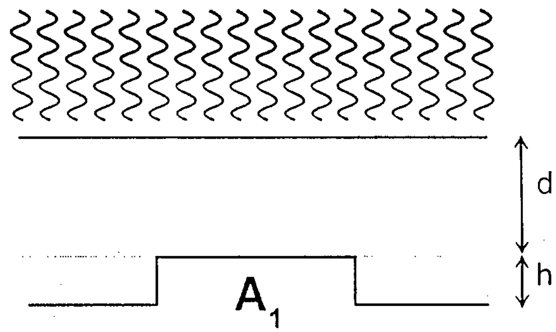
$$\Delta T(t) = \frac{Q}{\rho_1 c_1 \cdot d(r_1 + b\cdot r_1 r_2 - a_1)} \cdot \left(e^{-\frac{a_1}{Rd}\frac{k}{\rho_1 c_1}t} - e^{-\frac{r_1(1+br_2)}{Rd}\frac{k}{\rho_1 c_1}t} \right)$$

$$\boxed{\Delta T_{peak} = Q\cdot\left(\frac{1}{d}-\frac{1}{t_o}\right)\frac{\rho_2 c_2}{\rho_1 c_1}\frac{d+h}{(d\rho_1 c_1 + h\rho_2 c_2)} \cdot \left[\frac{a_1}{r_1(1+br_2)}\right]^{\frac{1}{1-\frac{a_1}{r_1(1+br_2)}}}}$$

$$a_1 = \frac{k_L}{k}\frac{A_d}{A} \qquad a_2 = \frac{k_L}{k}\frac{A_h}{A}$$

$$r_1 = \frac{R}{d+h} \qquad r_2 = \frac{d}{h} \qquad b = \frac{\rho_1 c_1}{\rho_2 c_2}$$

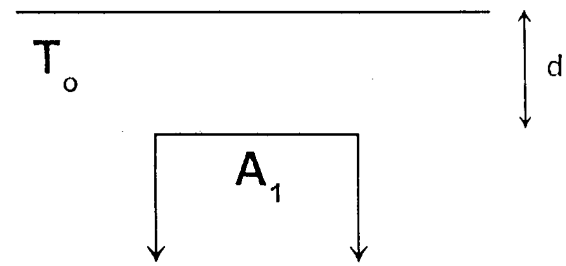
$$Q = J\cdot A\cdot t$$



$$\Delta T(t) = \frac{J}{a\cdot k}\frac{d+h}{(1+r)(1+r-a)} \cdot \left\{ (1+r)(1-e^{-\frac{a}{d(d+h)}\frac{k}{\rho c}t}) - a(1-e^{-\frac{1+r}{d(d+h)}\frac{k}{\rho c}t}) \right\}$$

$$\boxed{\Delta T(t\to\infty) = \frac{J}{a\cdot k}\cdot h}$$

$$a = \frac{k_L}{k}\frac{A_L}{A}\frac{d+h}{R} \qquad r = \frac{d}{h}$$



$$\Delta T(t) = \frac{Q}{\rho c\cdot d(AkR + A_d k_1 d)}\frac{kR}{} \left(e^{-\frac{b}{d^2}\frac{k}{\rho c}t} - e^{-\frac{1}{d^2}\frac{k}{\rho c}t} \right)$$

$$\boxed{\Delta T_{peak} = \frac{Q}{\rho c}\frac{kR(b-1)}{d(dA_d k_1 + RAk)}\cdot[b]^{\frac{b}{1-b}}}$$

$$t_{peak} = \frac{\rho c}{k}\frac{d^2}{b-1}\ln b$$

$$b = \frac{k_1}{k}\frac{A_d}{A_1}\frac{d}{R}$$

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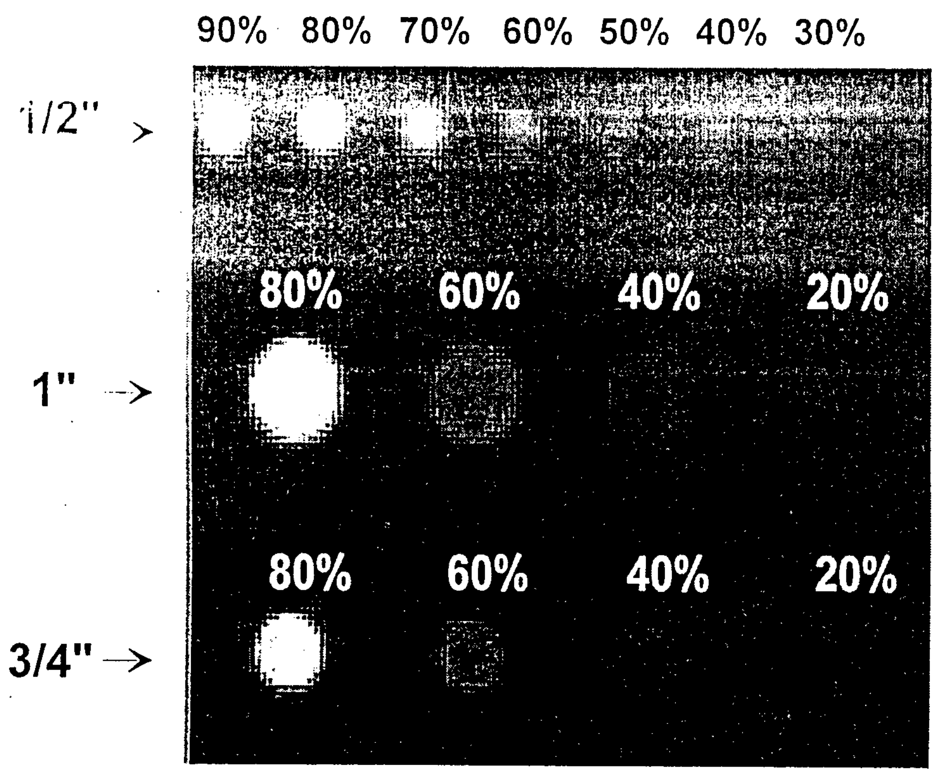
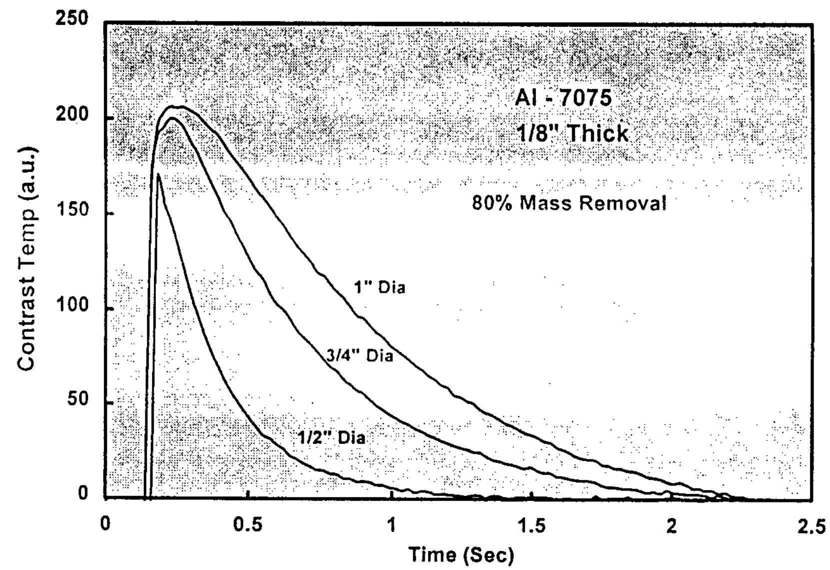
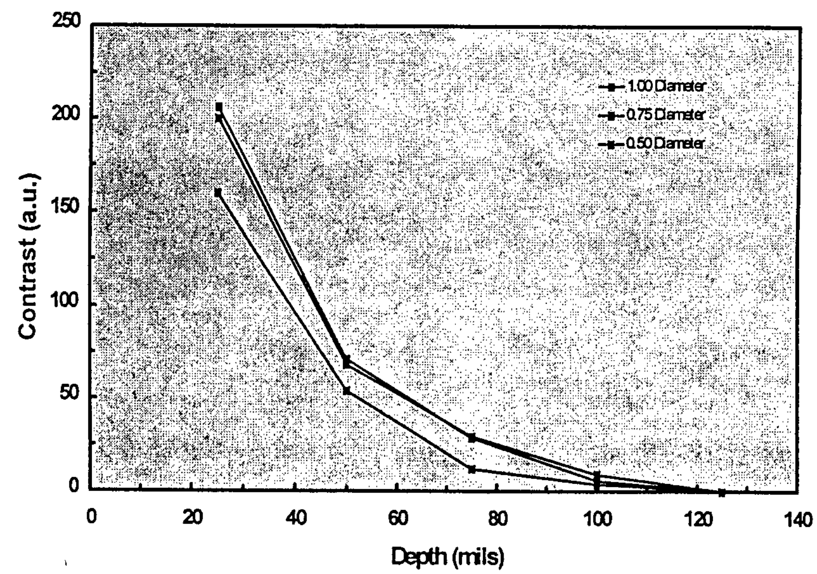
EXPERIMENTAL DATA
(80% mass removal)

NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING





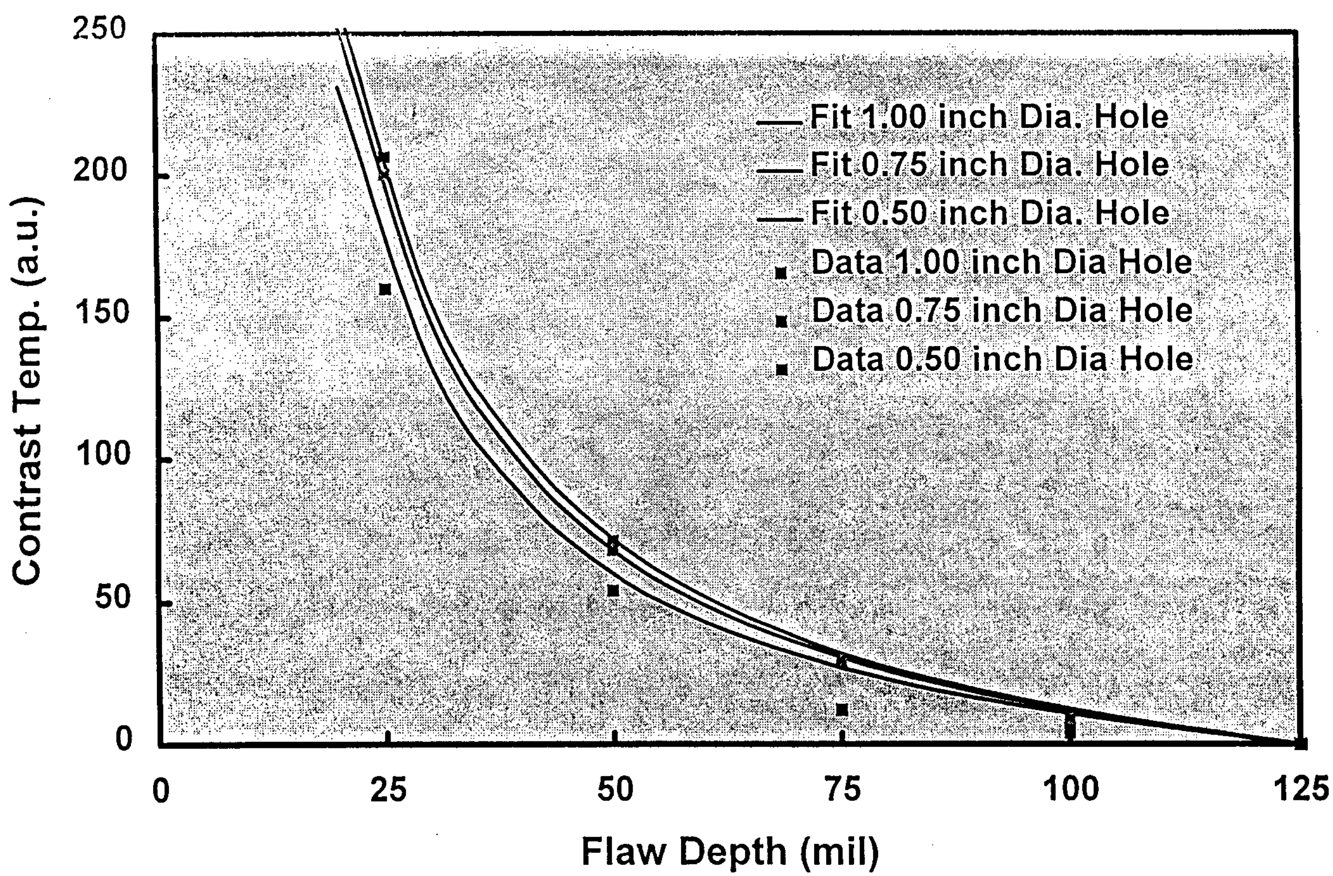
PEAK TEMP. vs DEPT



MODEL CORRELATION
(effects of defect size)

$$\Delta T_{max} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right) \cdot \left(\frac{a \cdot h}{t_o}\right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$

Effects of Radii



MODEL TIME-RESPONSE PREDICTIONS
(varying defect sizes and locations)

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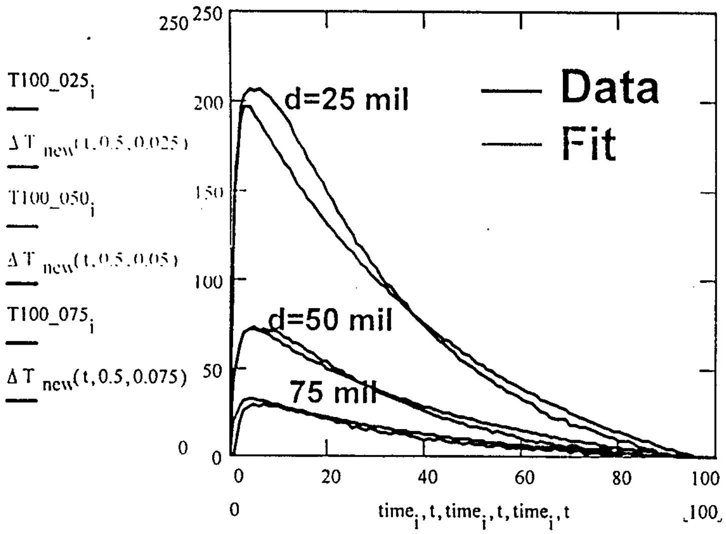
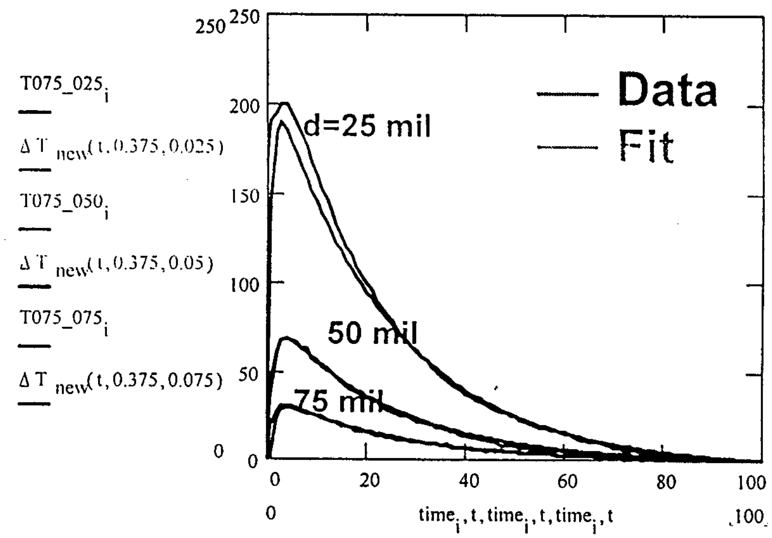
NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING

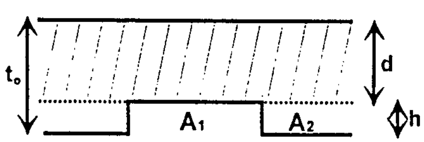
Dia = 1.00"

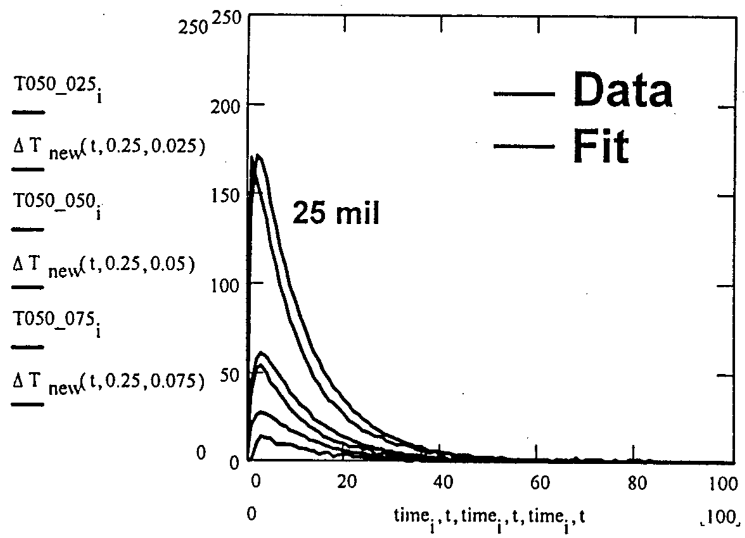


Dia = 0.75"



Dia = 0.50"

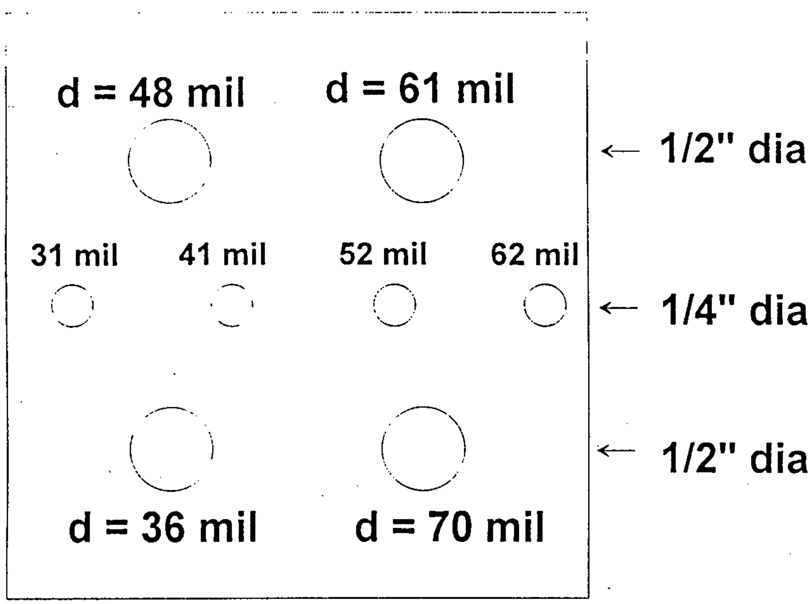




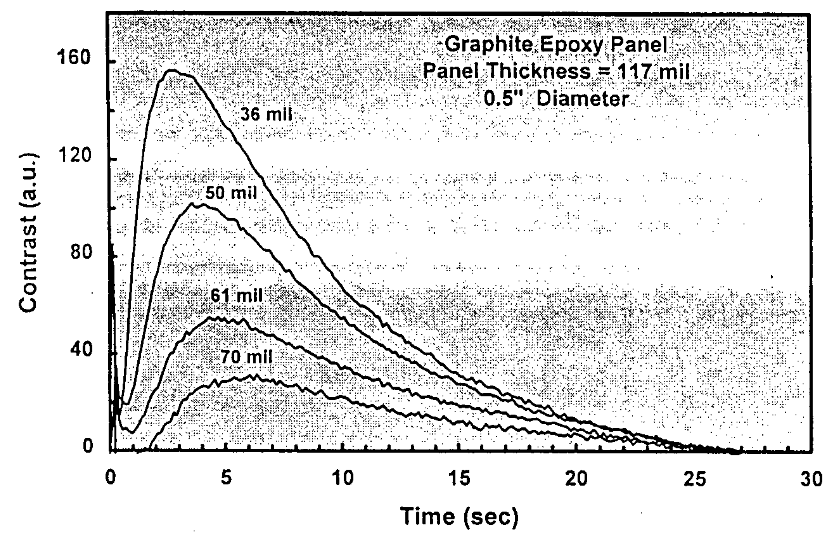
$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1 - a + r)} \times \left(e^{-\frac{a}{d(d+h)}\frac{k}{\rho c}t} - e^{-\frac{1+r}{d(d+h)}\frac{k}{\rho c}t} \right)$$

GRAPHITE EPOXY COMPOSITE PANEL

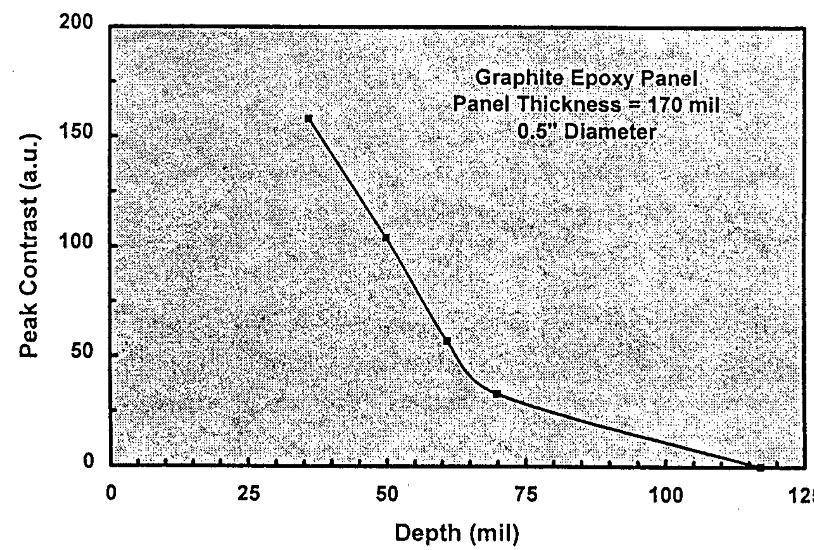
t = 117 mil



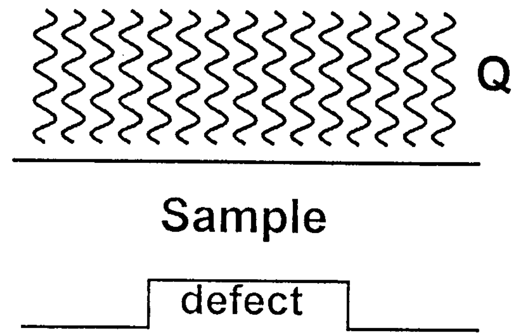
CONTRAST vs TIME

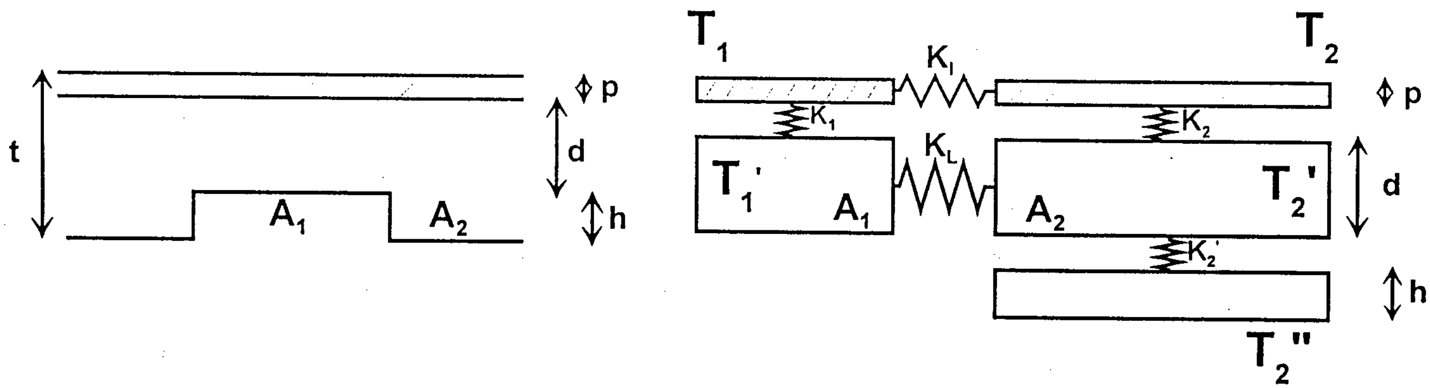


PEAK CONTRAST vs DEPTH



SIMPLE FINITE ELEMENT APPROXIMATION





$$\rho \cdot A_1 \cdot p \cdot c \cdot \frac{dT_1}{dt} = k \cdot A_1 (T_1' - T_1) + k_L \cdot A_p (T_2 - T_1)$$

$$\rho \cdot A_2 \cdot p \cdot c \cdot \frac{dT_2}{dt} = k \cdot A_2 (T_2' - T_2) + k_L \cdot A_p (T_1 - T_2)$$

$$\vdots$$

$$\rho \cdot A_2 \cdot h \cdot c \cdot \frac{dT_2''}{dt} = k \cdot A_2 (T_2' - T_2'')$$

k = Effective Contact Normal Thermal Conductivity

k_L = Effective Contact Lateral Thermal Conductivity

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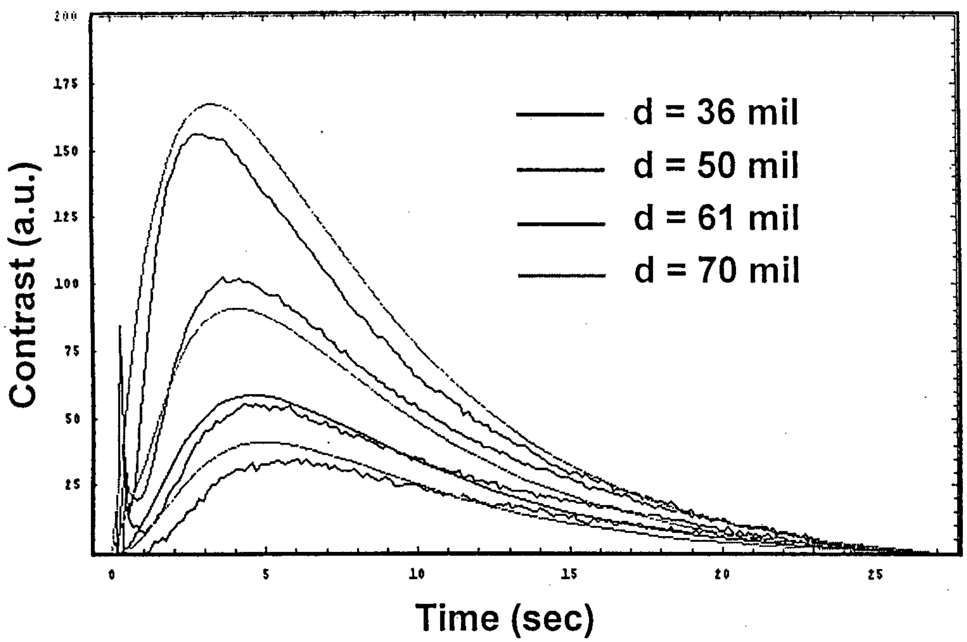
FITTING RESULTS

NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING

GRAPHITE EPOXY COMPOSITE

117 mil Thick



PEAK CONTRAST vs DEPTH